



National Aeronautics and
Space Administration



Full Scale Advanced Systems Testbed (FAST): Capabilities and Recent Flight Research

Aerospace Control and Guidance Systems Committee
Meeting #113

March 12, 2014








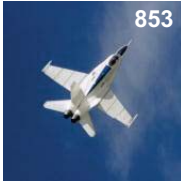
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Flight Control Research at DFRC Using the F/A-18 RFCS Capability



| Systems Research Aircraft (SRA) | | | | Full-Scale Advanced Systems Testbed (FAST) | | | |
|--|---|---|--|---|---|---|---|
| 1987-1996 | 1999 | 2000-2001 | 2005-2007 | 1996-2005 | 2009-2011 | 2012 | 2013 |
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| High-Alpha Research Vehicle (HARV) | SAAB JAS-39 Mini-Stick | Autonomous Formation Flight (AFF) | Autonomous Airborne Refueling Demonstration (AARD) | Active Aeroelastic Wing (AAW) | Intelligent Resilient Aircraft Control (IRAC) | Intelligent Control for Performance (ICP) | Launch Vehicle Adaptive Controls (LVAC) - - - Tao Sensors |
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Research Motivation of 853 FAST



- ◆ **Flight experimentation allows a researcher to substantiate or invalidate their assumptions and intuition about a new technology or innovative approach**
- ◆ **Data early in a development cycle is invaluable for determining which technology barriers are real and which ones are imagined**
- ◆ **Data for a technology at a low TRL can be used to steer and focus the exploration and fuel rapid advances based on real world lessons learned**
- ◆ **It is important to identify technologies that are mature enough to benefit from flight research data and not be tempted to wait until we have solved all the potential issues prior to getting some data**
 - Sometimes a stagnated technology just needs a little real world data to get it going
- ◆ **One trick to getting data for low TRL technologies is finding an environment where it is okay to take risks, where occasional failure is an expected outcome**
 - Learning how things fail is often as valuable as showing that they work
- ◆ **FAST has been architected to facilitate this type of testing for control system technologies, specifically novel algorithms and sensors**
 - Rapid prototyping with a quick turnaround in a fly-fix-fly paradigm
 - Sometimes it's easier and cheaper to just go fly it than to analyze the problem to death
- ◆ **The goal is to find and test control technologies that would benefit from flight data and find solutions to the real barriers to innovation**



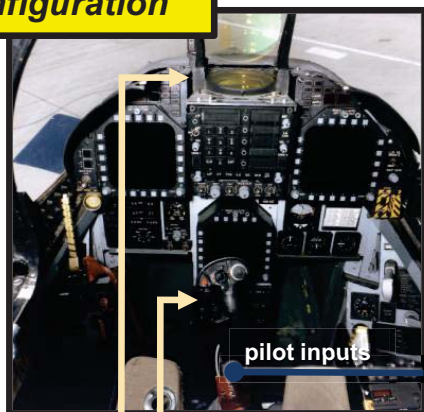
853 FAST System Architecture



Envelope Monitoring and Fault Checking

Pilot monitoring and in-flight experiment configuration

Sensors



pilot inputs

ARTS HUD ILS Needle Commands

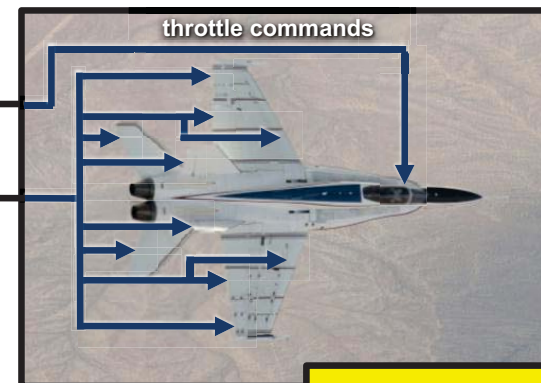
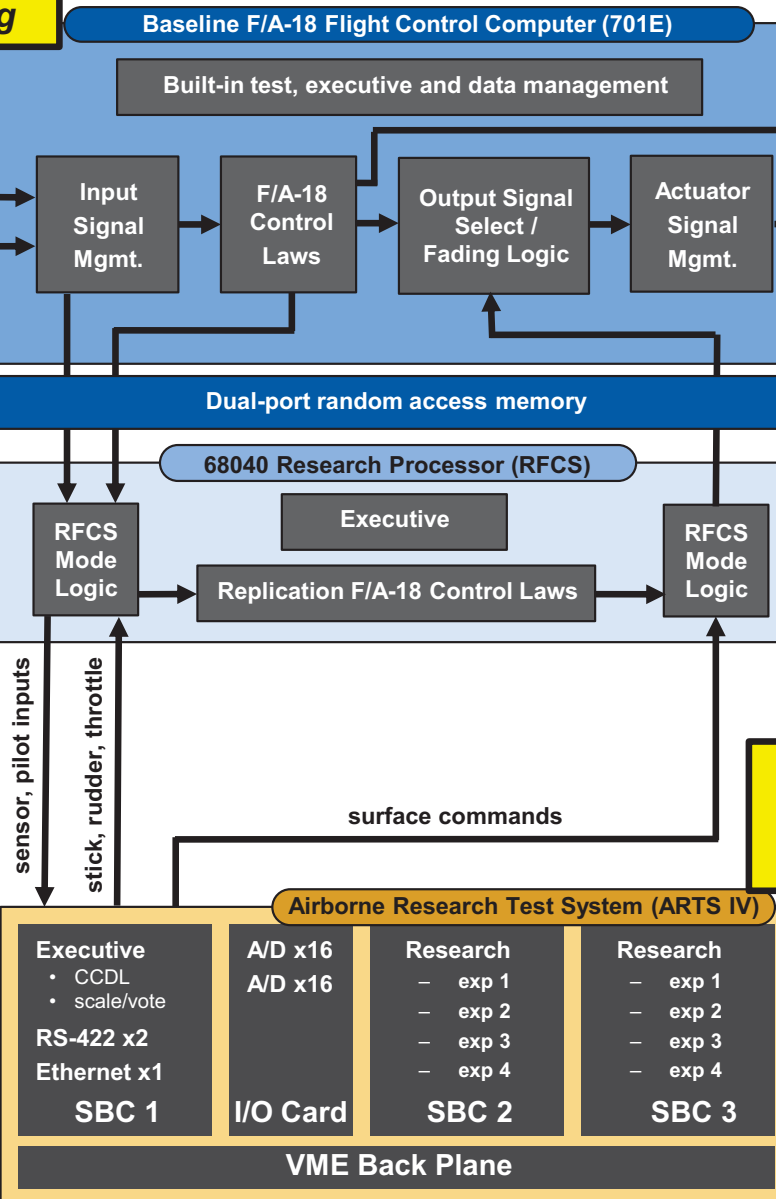
ARTS Status Display

Research Sensors

Instrumentation

EGI

AIC



throttle commands

Full-Range Command Authority

Experiments auto-coded from Matlab®





Key Research Capabilities and Rapid Prototyping Features



◆ Research Capabilities

- High performance tightly coupled research flight control computers
 - Quad redundant 68040 processors inside the production FCC's
 - Ada programmable
 - Dual redundant Power PCs linked via 1553 to the production FCC's
 - C Code, and Autocoded Simulink
- The research systems have full authority over the vehicle control surfaces and throttle positions
- Extensive research instrumentation system that can be easily expanded and utilized as feedback sensors for control laws
- Experiments have the ability to provide basic pilot queuing via the ILS needles

◆ Design Features that Enable Rapid prototyping

- Protected envelop
 - Allows for minimal testing prior to flight
 - Full envelop capability available with additional testing and verification for closed loop control experiments (Open loop experiments require no additional testing)
- Robust production control laws, systems, and vehicle structure
- Autocoding capability
- High fidelity hardware in the loop simulation



Recent Past Experiments



◆ Integrated Resilient Aircraft Control (IRAC)

- Performed for NASA's Aviation Safety Program
- The objective was to determine how adaptive control technologies could be employed to make aircraft more robust to uncertain environments and damage

◆ Intelligent Control for Performance (ICP)

- Performed for NASA's Environmentally Responsible Aircraft Program (ERA)
- The objective was to explore how intelligent control technologies could be utilized to reduce fuel burn for aircraft in cruise

◆ Launch Vehicle Adaptive Controls (LVAC)

- Performed for the Space Launch System (SLS) program with the help of the NASA Engineering and Safety Center (NESC) and the Game Changing Developments (GCD) program
- The objective was to demonstrate inflight the benefits of a specific adaptive control technology being implemented as part of the baseline design for SLS, and to broaden the knowledge base for adaptive controls as applied to flight vehicles in general



Motivation for Testing Adaptive Flight Controls



◆ Motivation for adaptive flight control technologies

- Self tuning could accelerate development, and increase robustness to damage and environmental uncertainty
- Adaptability becomes more important as vehicle configurations become more and more complex and the interactions between their systems become more complicated

◆ Barriers to integrating these technologies in production flight vehicles

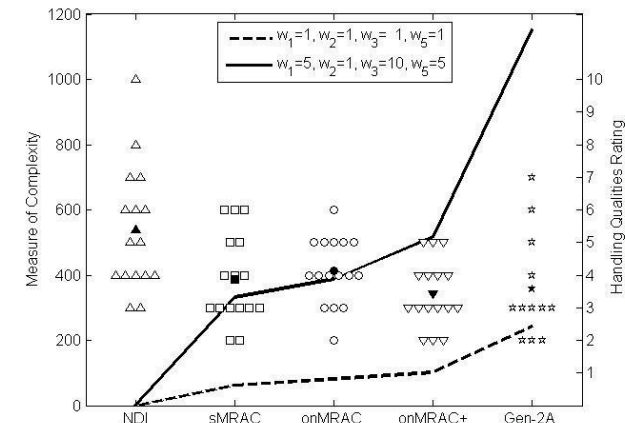
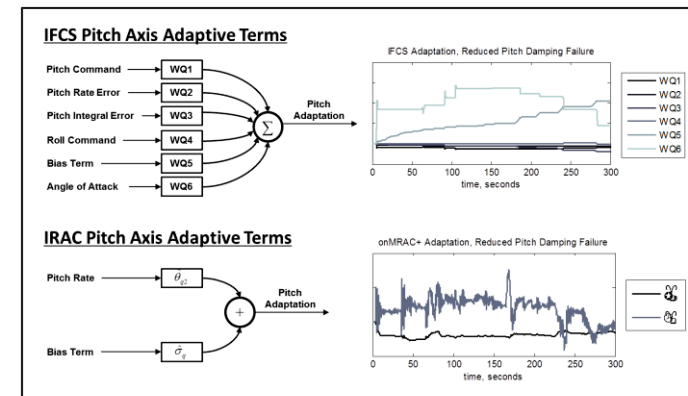
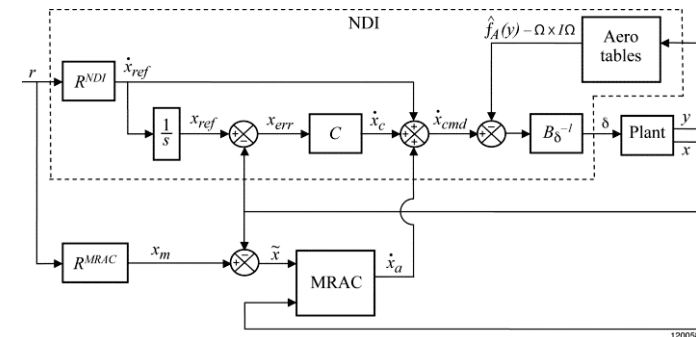
- Complexity of verification and validation
- Lack of intuition and experience designing them and lack of knowledge about how they fail
- Concerns about how they interact with aircraft structure
- Lack of an understanding of how pilots interact with and perceive them as they are both adapting to the behavior of the vehicle



Integrated Resilient Aircraft Control (IRAC)



- ◆ In 2009, the IRAC project consulted with representatives from Academia, Industry and other Government agencies to develop objectives for a new flight experiment.
 1. Demonstrate a Simple yet Effective Adaptive Control Implementation
 2. Study Pilot Interaction with Adaptive Systems
- ◆ In 2011, ten research flights were completed on the Full-Scale Advanced Systems Testbed (FAST)
 - Successfully demonstrated adaptation to simulated failures and aircraft damage.
 - Achieved similar performance and handling quality improvements to the IFCS design, with a significantly less-complex adaptive controller.
 - Uncovered several modes of adverse pilot vs. adaptive controller interaction, and identified design fixes.





IRAC Accomplishments

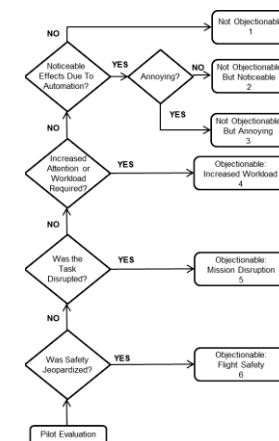
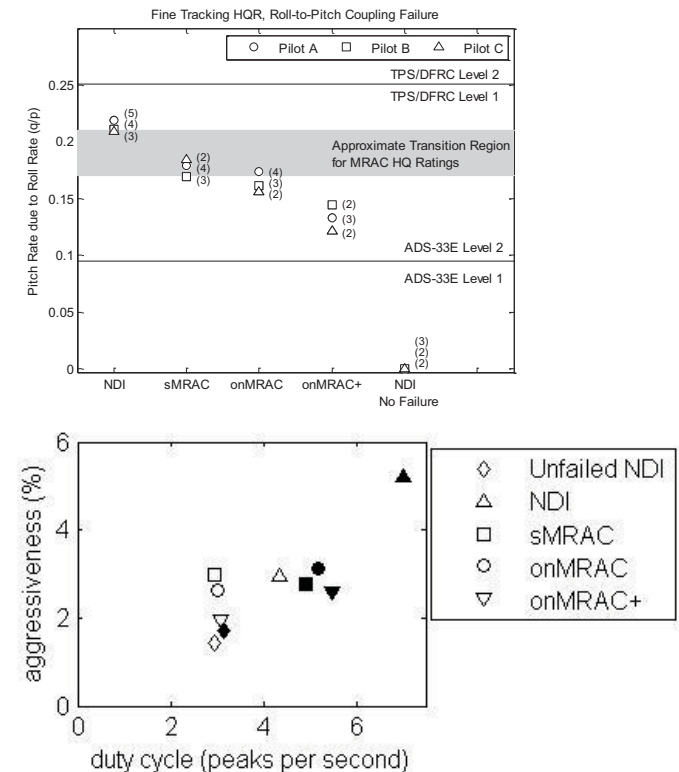


◆ Innovations

- Optimal Control Modification (OCM) Term (developed by Nhan Nguyen at NASA Ames)
- Cross-Coupling Handling Qualities Metric for Fixed-Wing Aircraft
- Adaptive Pilot Model
- Controller Complexity Metric
- Pilot Workload Metrics
- Evaluation of an Automated Systems Nuisance Scale adaptive controllers (originally developed for Auto-GCAS)

◆ Products

- 4 AIAA Conference Papers on Flight Results
- 2 SETP / SFTE Conference Papers
 - Flight Test Techniques and Risk Mitigation
- 3 NASA Technical Memorandums
 - Adaptive Pilot Model
 - Low-Complexity MRAC Design
 - Complexity and Pilot Workload Metrics
- OCM Patent Application (Nguyen)



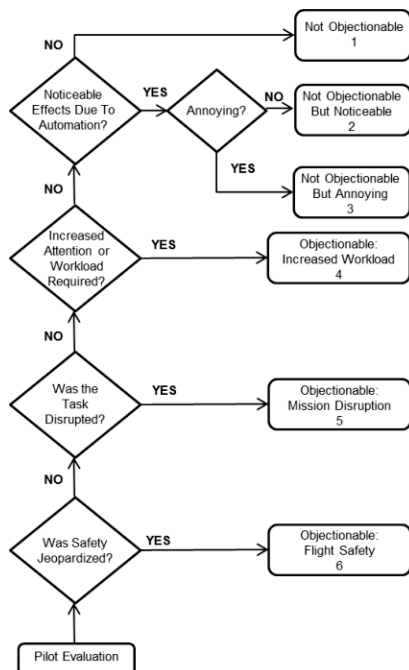


New Metrics for Mixed Autonomy



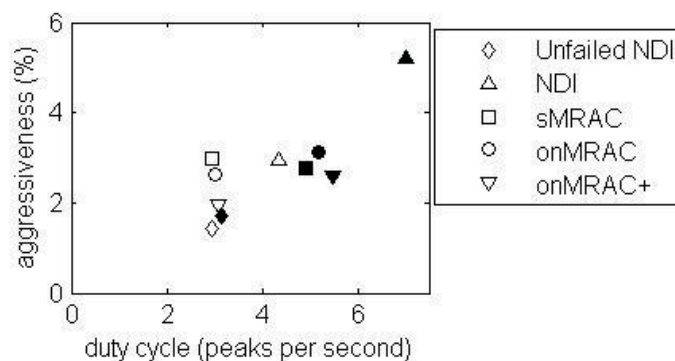
◆ Nuisance Scale

- Developed as part of the Autonomous Collision Avoidance Technology (ACAT) project
- Structure based on the Cooper-Harper Rating (CHR) and PIO rating scales
- Used to evaluate the IRAC adaptive controllers without failures



◆ Pilot Workload Metrics

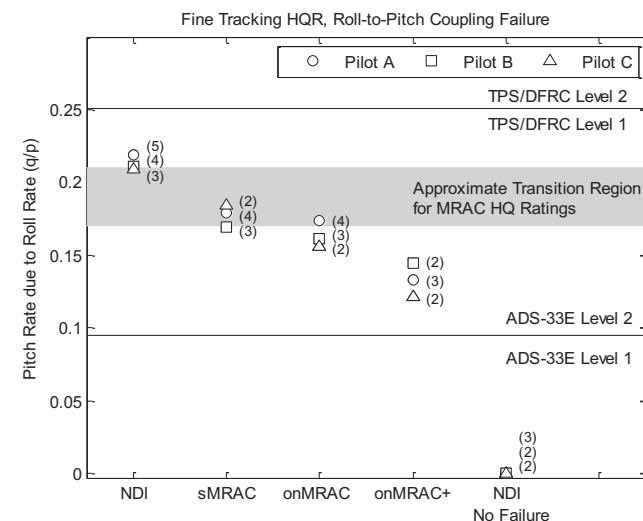
- Pilot workload is a large factor in the qualitative CHR scale
- To better predict changes in pilot workload resulting from controller adaptation, a quantitative pilot workload metric was created
- The metric is a cross-plot of pilot aggressiveness and duty cycle
- Under the IRAC project, the metric revealed differences between individual pilots in controller-related workload



Pilot A (open) and Pilot B (solid) during 2g air-to-air tracking with a reduced pitch damping failure

◆ Cross-Axis Coupling HQR

- Traditional fixed-wing design metrics predict handling qualities ratings for individual axes
- IFCS and IRAC flights showed that coupling between axes is a significant factor in pilot evaluations
- Based on a modified rotary-wing handling qualities scale
- Showed a correlation between axis coupling and IRAC pilot handling qualities ratings





Intelligent Control for Performance (ICP) Objectives



♦ Motivation for innovation

- US domestic flights in 2011:
 - 12.1 billion gallons of fuel
 - 114.6 million metric tons of CO2 equivalent
- The current state of the art for aircraft trim utilizes scheduled surface positions based on a priori designs from: models, wind-tunnels, and flight-test data
- Fixed schedule trim solutions may not address:
 - Operating in off-nominal flight conditions
 - Subtle manufacturing differences compared to aircraft of the same type
 - Modifications such as winglets, external stores, blisters, engine upgrades, or repairs
 - Increased flexibility with age, leading to a different wing shapes under load

♦ Solution approach

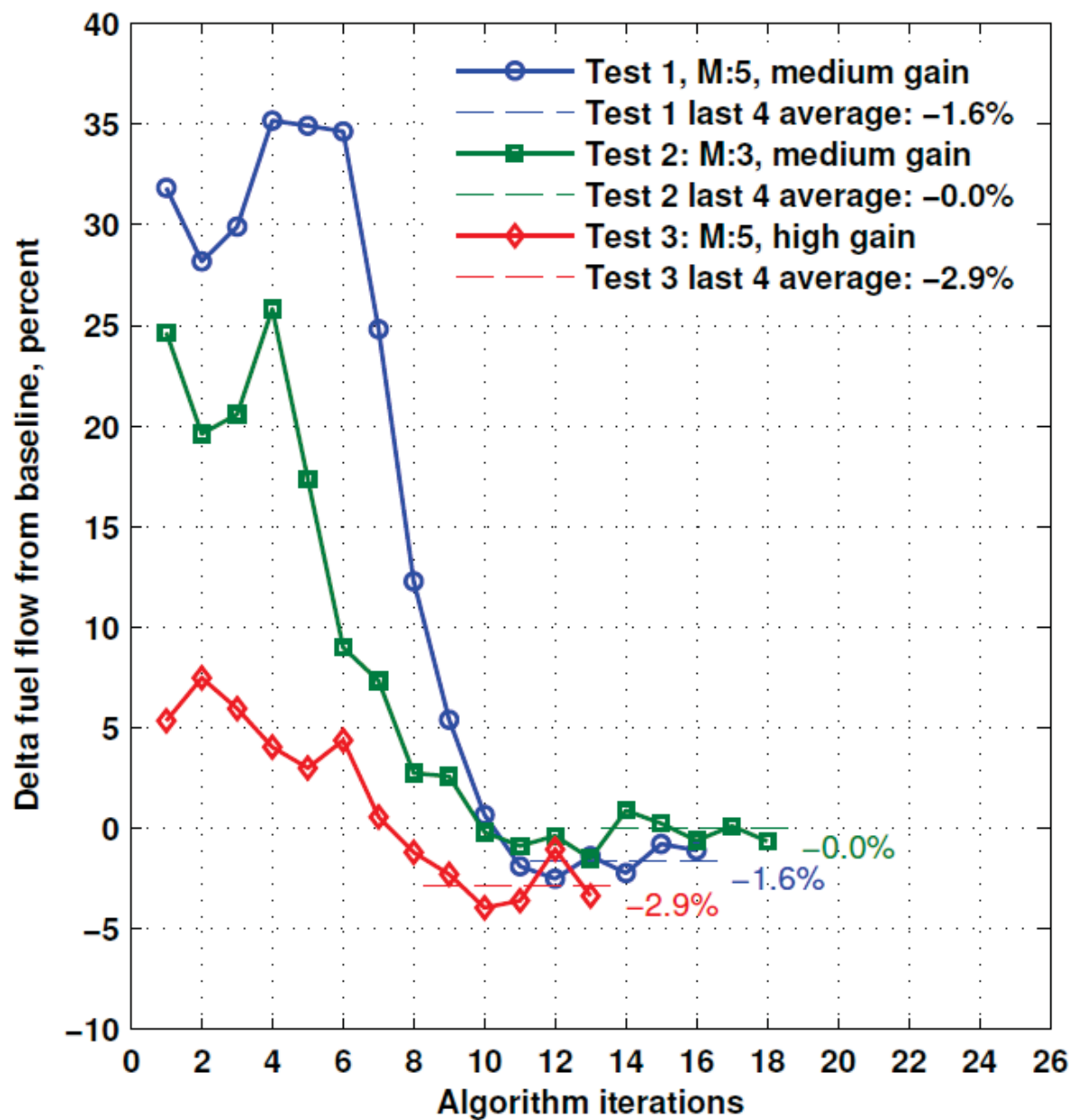
- Use real-time performance measurements to tune the longitudinal trim surface positions
- Utilize a Kalman filter to estimate the shape of the fuel flow vs. various surface positions implemented in a peak seeking control architecture

♦ Why does a flight experiment on an F-18 make sense?

- Modeling this problem is really hard and involves complex interactions between control surfaces, engine performance, inlet characteristics, sensor characteristics, atmospheric behavior, ...
- We came to the conclusion it was just easier to go fly it and see what worked and what didn't rather than try and model everything
- With the FAST architecture it was cheap, safe, and expedient to build the experiment and go get some data to help inform the technology development process



ICP Flight Data





Intelligent Control for Performance (ICP) Key Outcomes



- ◆ Results after six research flights
 - Algorithm consistently converged on low fuel flow trim configurations from any starting point
 - Trim setting found requiring approximately 3% less fuel flow vs. the baseline F/A-18A
 - Fuel savings of 1% to 2% were more typical
 - Research-grade fuel flow meters were not required to attain these levels of fuel savings
 - Similar results were attained utilizing the production fuel flow measurements, and the commanded steady state throttle position as the “cost” measurement
 - Algorithm performed well at two flight conditions near max loiter and on the back side of the power curve
 - Pilots noted that algorithm did not impact ride quality
- ◆ Key questions still to be answered
 - How does the algorithm handle external stores, and asymmetric configurations
 - Does it work in moderate turbulence
 - Can it be used to minimize wave drag at high subsonic and supersonic speeds
 - What are some of the practical limitations to the number of control surface positions it can optimize
- ◆ Tech transfer of ICP to US Navy is ongoing



Launch Vehicle Adaptive Control (LVAC)



- ◆ **Goal:** Advance the TRL of the SLS Adaptive Augmenting Controller (AAC) through full-scale flight testing on a research aircraft in a relevant environment
- ◆ **Multi-Center, Multi-Organization Partnership**
 - Dryden Flight Research Center
 - Marshall Space Flight Center
 - NASA Engineering and Safety Center (NESC)
 - STMD Game Changing Development, Autonomous Systems
- ◆ **Schedule**
 - 24-Jan-2013: Project Start (DFRC-MSFC TTA signed)
 - 22-Aug-2013: Approval for First Flight
 - 12-Dec-2013: Flight Tests (6) Complete





Launch Vehicle Adaptive Controls (LVAC) Top Level Objectives

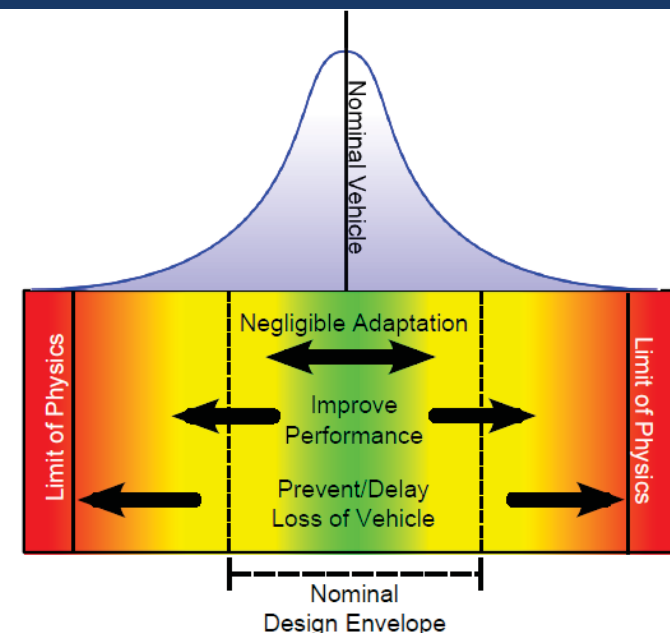


“GN&C issues are rarely the cause for launch vehicle failures. However, a review of historical launch vehicle data from 1990 to 2002 revealed that 41% of failures might have been mitigated by advanced GN&C technologies.” – J. Hanson et al.

- ◆ In the absence of vehicle or environmental uncertainty, a fixed-gain controller could be optimized prior to flight (no motivation for adaptation)
- ◆ Adaptive control provides additional robustness by using sensed data to adjust the gain on-line
- ◆ MSFC adaptive algorithm has three summary-level design objectives:
 1. “Do no harm”; return to baseline control design when not needed
 2. Respond to error in ability of vehicle to track commands to increase performance
 3. Respond to undesirable parasitic dynamics (i.e., control-structure interaction) to regain stability

SLS Vehicle Flight Control Design Challenges

- Large, highly flexible structure with minimal ground testing to characterize structural modes
- Massive propellant tanks with lightly-damped slosh modes
- Uncertain payload envelope with parasitic dynamics
- Highly optimized trajectories
- Complex thrust vectoring system with multiple, fully-actuated engines
- Aggressive robustness and redundancy requirements driven by human rating





Algorithm Flight Testing on FAST



◆ Flight characterization experiment contributions to the success of the SLS Program

- Advance the Technology Readiness Level (TRL) of the SLS AAC scheme early in the program
 - **The Adaptive Augmenting Controller (AAC) is the only part of SLS autopilot that has not been flight tested**
- Increase internal and external confidence in AAC
 - Software V&V and flight certification of the full-scale algorithm
 - Characterize the algorithm on a flight test platform that is dynamically similar to the launch vehicle
 - Manned flight test program

◆ Test objectives mirror the design objectives in order to fully vet the algorithm:

Objective 1: Minimal Adaptation in the Nominal Case

Objective 2: Improved Tracking Performance

Objective 3: Restrict Unstable Mis-Modeled Parasitic Dynamics to a Bounded Non-Destructive Limit Cycle

Objective 4: Explore Interactions between Manual Steering and the AAC





Dynamically Similar Trajectory



♦ Trajectory Description

- Zoom climb followed by pitch over maneuver lasting ~75 seconds at a constant pitch rate of -0.75 deg/sec

♦ Similarities to SLS boost trajectory

- Pitch axis dynamic response (Provided by NDI)
- Attitude rate and pitch attitude command shape
- Time scaling

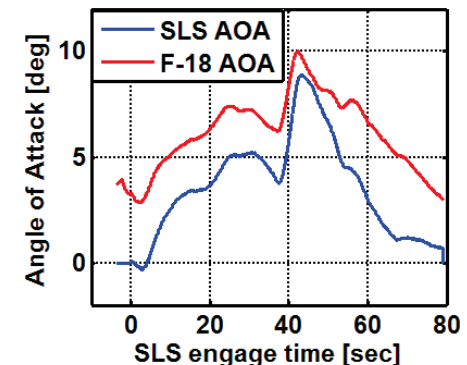
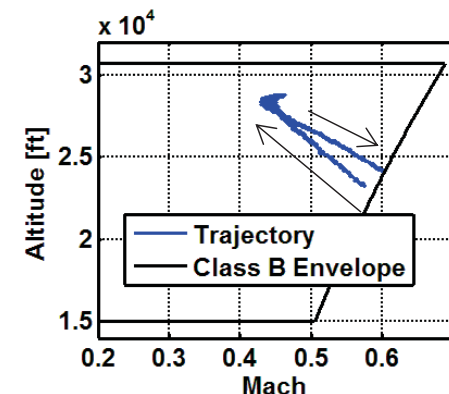
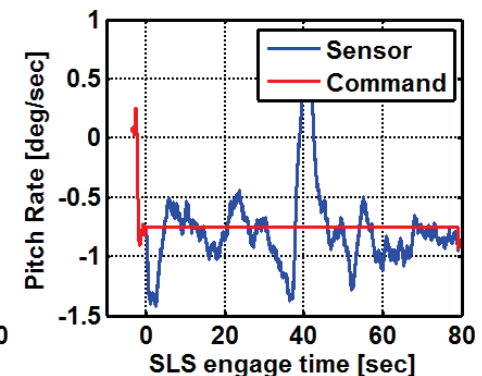
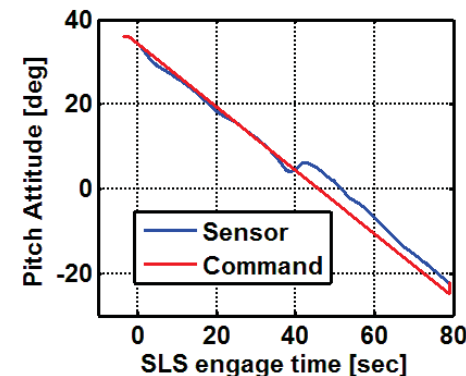
♦ Differences from SLS boost trajectory

- Actual vehicle Mach, altitude, and dynamic pressure profile
 - Simulated within the SLS reference model
- Lift curve slope
 - angle of attack similarity achieved by NDI rigid body matching
- Actual vehicle normal acceleration
 - Must disable load relief loop

♦ Other Benefits of the platform

- Number of test points and total test time
- Wide variety of failure/off nominal scenarios including the real F-18 fuselage mode
- Pilot in the loop testing

Test Case 7 AAC on (Hardover, Wind Shear)

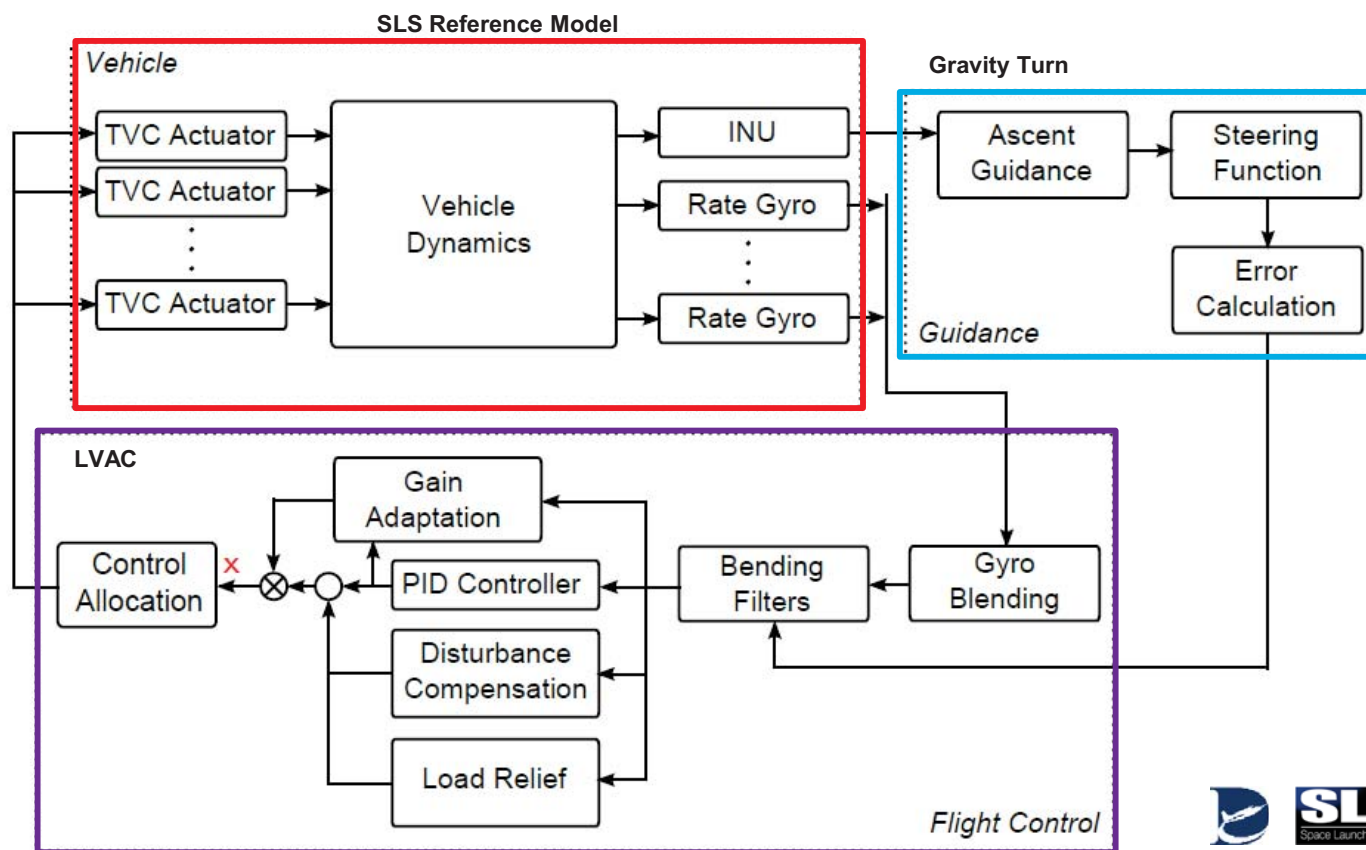




LVAC Implementation of Flight Controller



- ◆ *The SLS production flight software prototype is the same source code executing on the ARTS platform for this experiment*
- ◆ MSFC has developed SLS reference model (plant+controller) in Simulink to be integrated within the Dryden tools, then autocoded to ARTS platform
 - SLS C-code control system written as an S-function to be integrated with the Simulink reference model and FAST tools

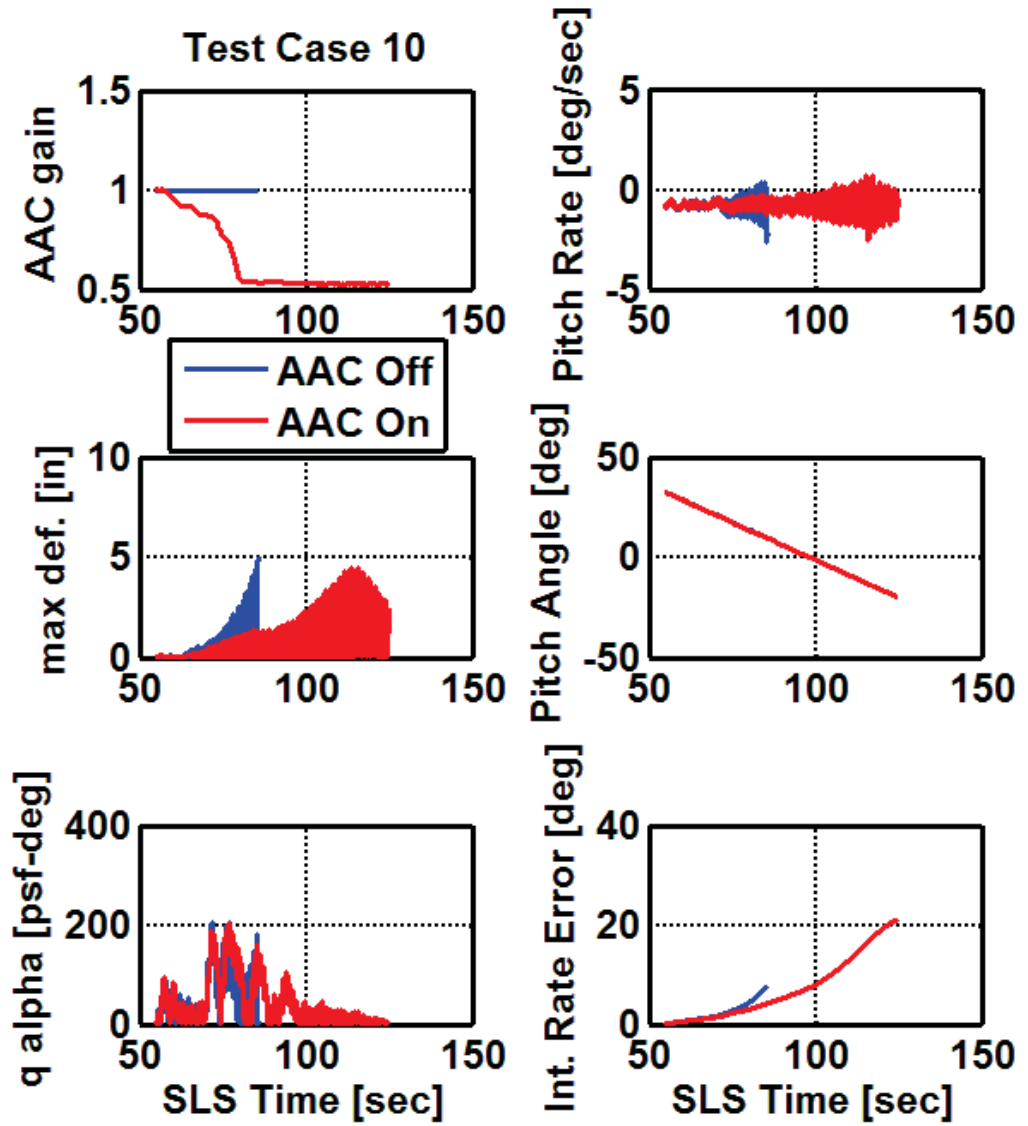




Restrict Parasitic Dynamics to a Bounded Non-Destructive Limit Cycle (Structural Mode)



- ◆ Demonstrate Restriction of Unstable Parasitic Dynamics
- ◆ TC 10 – Structural Instability
- ◆ Successfully demonstrated the objective
- ◆ Anomalies
 - Ailerons (used to simulate SLS structural mode) were more effective than predicted in the simulation
 - Resulted in a slightly more unstable mode than predicted
 - Did not affect the successful completion of test condition

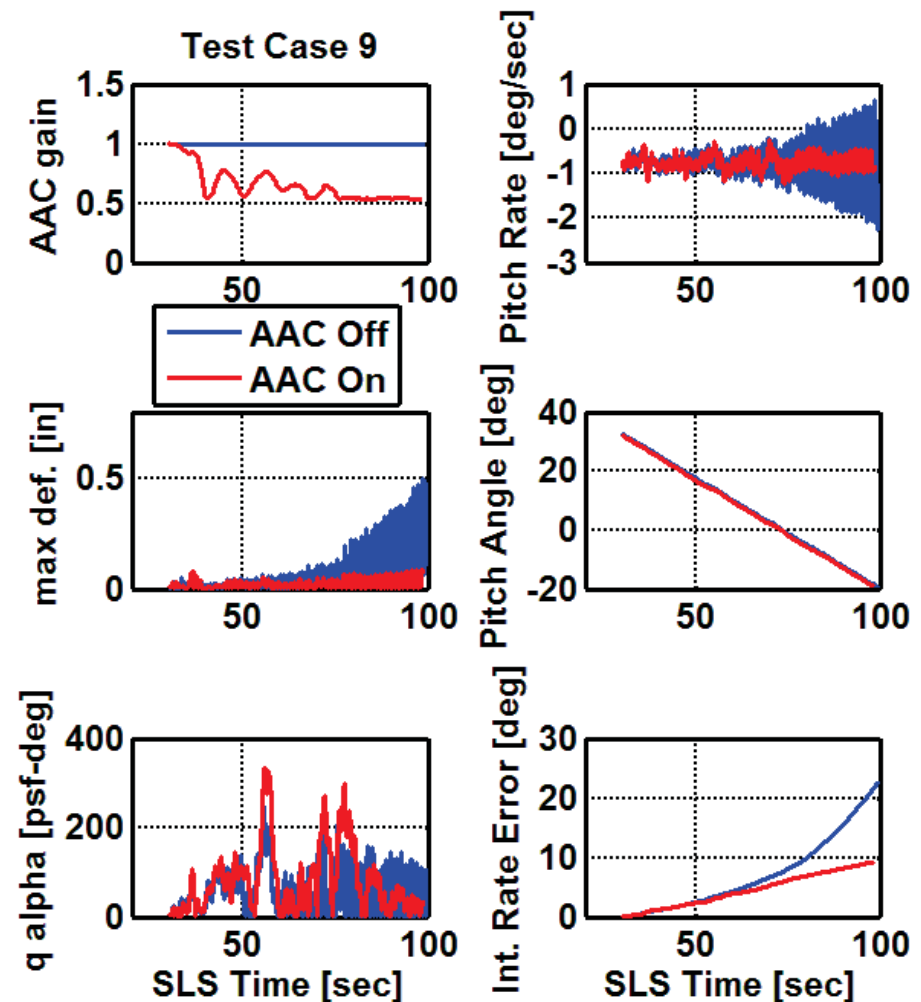




Restrict Parasitic Dynamics to a Bounded Non-Destructive Limit Cycle (Slosh Mode)



- ◆ **Demonstrate Restriction of Unstable Parasitic Dynamics**
- ◆ **TC 9 – Light/Fast Vehicle with Slosh Instability**
- ◆ **Successful demonstration of the objective**
- ◆ **Anomalies**
 - Simulated slosh mode frequency very near the bare airframe short period.
 - The coupled interaction caused an unexpected well damped but poorly attenuated mode
 - Predicted in the F-18 HILS
 - The AAC gain exhibited a previously unobserved behavior
 - Oscillatory behavior related to a trade between spectral content driving the gain down, tracking error driving the gain up, and the leakage term

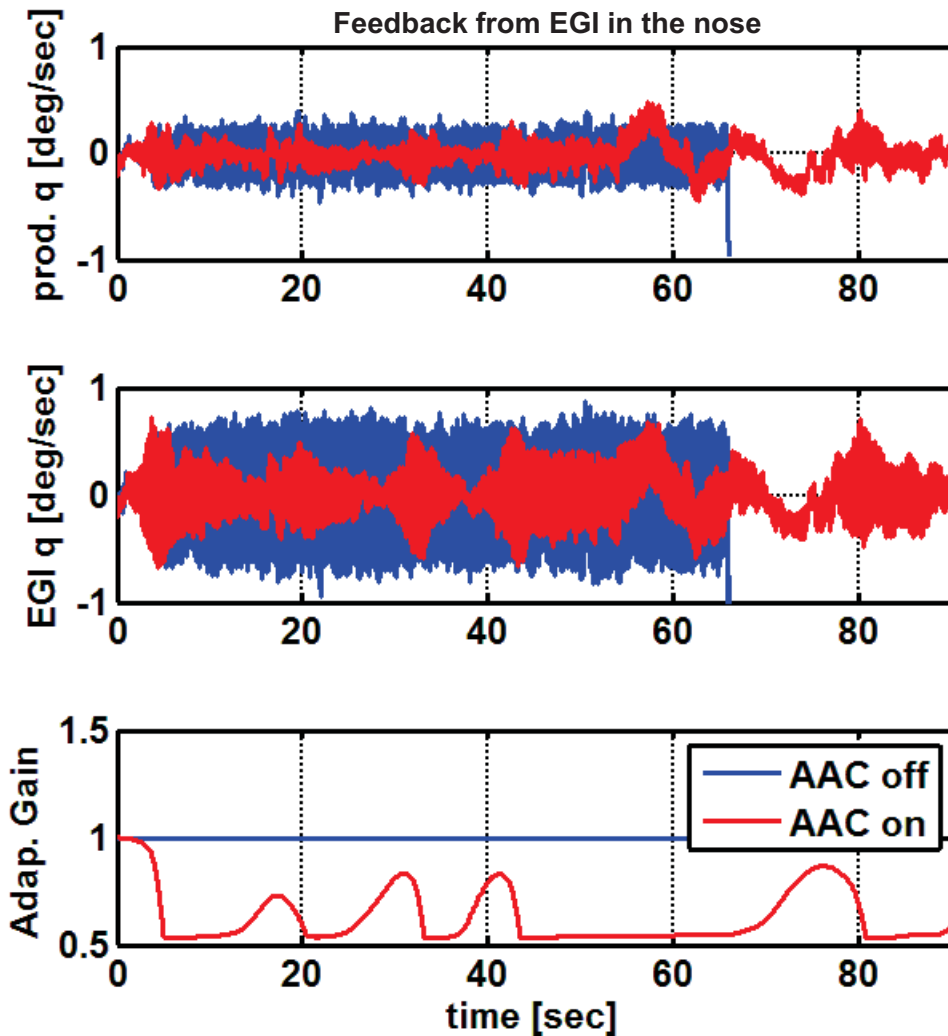




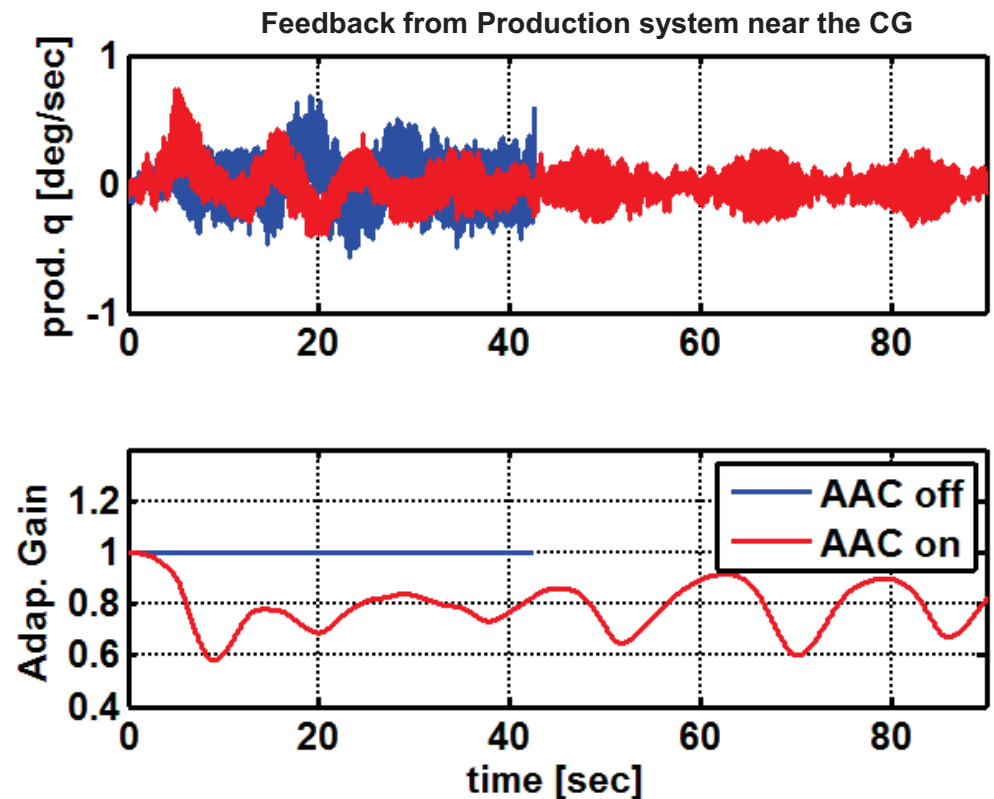
AAC Response to the Real F-18 Structural Mode



- ◆ Data from the first flight used to generate a test case that destabilized the SLS controller's response to the real F-18 first fuselage bending mode (the opposite of what control designers normally try to do)

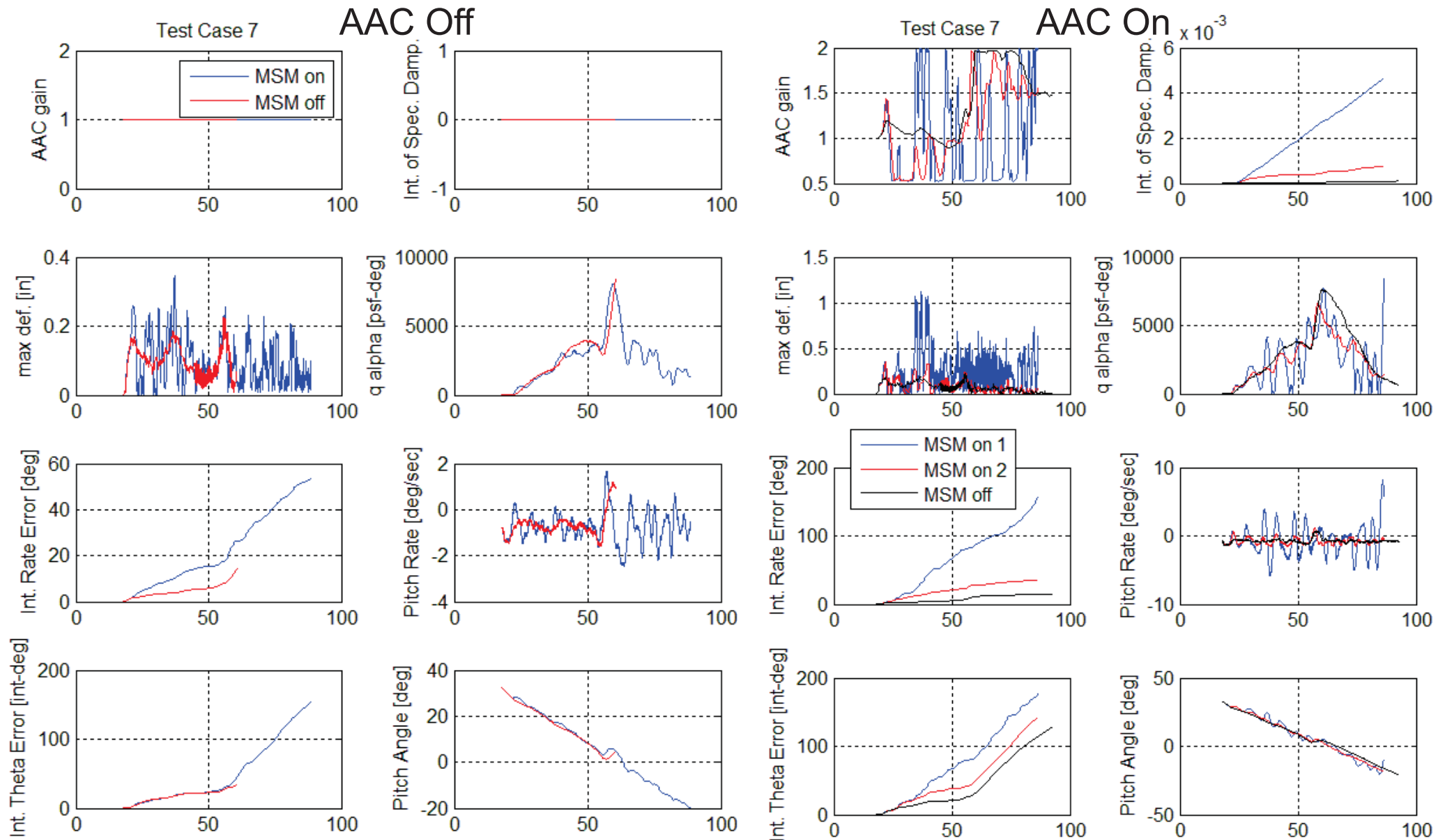


- ◆ Multiple sensor locations and fuel loadings tested
- ◆ AAC was effective at attenuating the mode, but did exhibit an oscillatory behavior that allowed the mode to return
- ◆ Caused by overshoots of the ideal gain due to the lag in the spectral damper term exacerbated by an imbalance in the adaptive terms for a parasitic mode of this shape





Manual Steering Mode and AAC Interactions





LVAC Key Outcomes



- ◆ **AAC as applied to the SLS provides significant benefit and all of the design objectives were demonstrated in flight:**
 - Minimal Adaptation in the Nominal Case, Improved Tracking Performance, Restrict Parasitic Dynamics
- ◆ **Benefits of the rigor of software development for flight**
 - A number of software bugs in the SLS code were uncovered because the team refused to ignore seemingly insignificant anomalies
- ◆ **Benefits of testing on a platform with the right balance of similarities and differences**
 - The response of the controller to non-zero initial body rates was improved as a result of a small initialization shortcoming discovered due to the nature of the test points on the F-18
 - Bugs in filter initialization were discovered due to the back to back repeat of test points
 - Limitations in the performance of the algorithm for well damped poorly attenuated modes was uncovered (not something that requires addressing for SLS)
- ◆ **Initial findings related to interactions between the pilot and the adaptive controller**
 - AAC and the piloted mode as implemented for this test complement one another for failures that require a gain reduction
 - For failures where pilot effectively wants to increase tracking performance (increase gain) the AAC algorithm erroneously interprets the pilot's aggressiveness as a parasitic mode and in effect fights the pilot by reducing the gain (PIO)
- ◆ **Preliminary generic finding for other applications of the adaptive architecture**
 - Delay in the rectifier drives a gain oscillation due to a delay in the spectral damper term for modes with relatively good damping but poor attenuation, which can be compounded by the design of the shape of adaptation rates at the edges and the trade between the leakage term and the other objectives





Upcoming Flight Experiment



◆ Optimal Control and Load Allocation (OCLA)

- An experiment that utilizes structural feedback to actively sense and limit structural overload while maintaining the desired dynamic response to pilot control inputs
- Internal Armstrong research funded primarily out of the Center Innovation Fund



Optimal Control Load Allocation Background



◆ Problem Statement

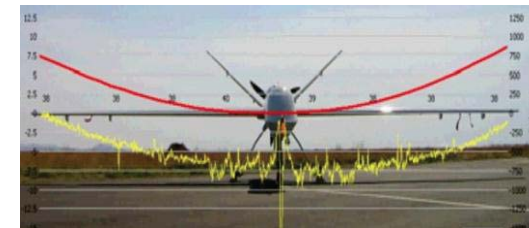
- ***Current aircraft designs utilize high design structural margins and fixed control allocation schemes to prevent structural overload for a priori operating conditions and maneuvers.***
 - Higher vehicle weight (more fuel burn)
 - Lack of adaptability to damage
 - Lack of robustness to flight outside of the design flight envelope (stall/spin)
 - No explicit guarantee of prevention of structural overload

◆ Possible Solution Concept

- ***Critical loads can be measured with either conventional foil strain gauges and more recently with fiber optics.***
- ***These sensors implemented as “pain” indicators in a control architecture with a “limp” reflex can be used to sense when a structure is being pushed to its limit, actively limit that load and redistribute control commands to surfaces and structure with available margin***

◆ Key Benefits

- ***Enables lighter weight aircraft structure***
- ***Automatically adapts to many damage scenarios***
- ***Increases aircraft robustness in loss of control scenarios***
- ***Enables advanced control techniques***





Optimal Control Load Allocation Scope



- ◆ **Explore the merits of Optimal Control Allocation with structural feedback in flight on a full scale piloted vehicle (1-2 Flights)**
 - Limited envelope allows rapid prototyping
- ◆ **Feedback strain gauge measured aileron hinge moment**
 - Utilizes ARTS ability to feedback research instrumentation data to a control law
- ◆ **Utilize measured strain within an optimal control allocator to actively limit the load on aileron attachment rivets to specified values maintaining aircraft handling qualities and performance**
- ◆ **Utilizes the same baseline control architecture as IRAC, and ICP. All three technologies could be easily combined in one control structure.**
- ◆ **Objectives:**
 - Objective 1: Limit the aileron motion subject to a defined load constraint.
 - Objective 2: Maintain the roll axis frequency response of the controller that does not utilize structural load as a constraint.
 - Objective 3: Maintain the handling qualities ratings of the controller that does not utilize structural load as a constraint



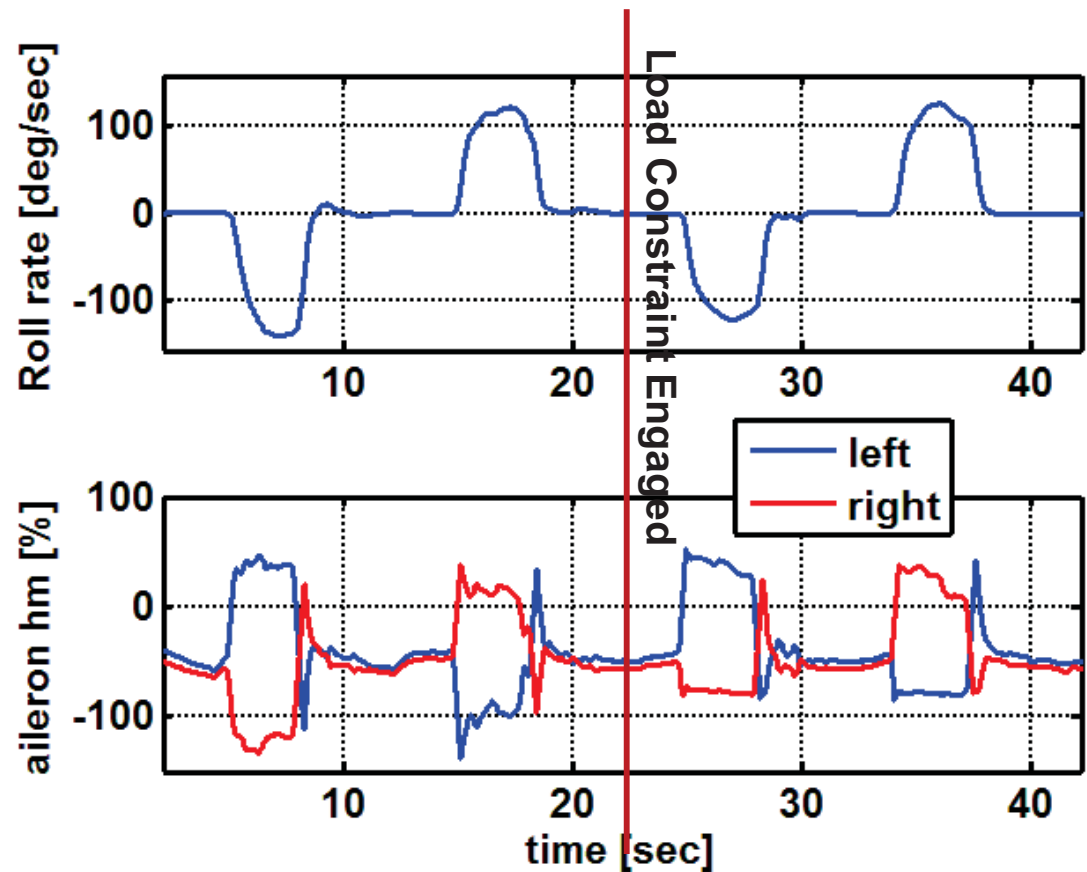
Critical load for the OLCA experiment
(maintenance issue and cost)



OCLA Status



- ◆ All design reviews complete
- ◆ Hazard analysis complete
- ◆ Experiment HILS V&V complete
- ◆ Flights scheduled for April pending completion of some routine aircraft maintenance





Summary



◆ Platform

- The FAST vehicle is a flexible laboratory for nascent technologies that would benefit from early life cycle flight research data
- It provides a robust and safe environment where innovative techniques can be explored in a fly-fix-fly rapid prototyping paradigm

◆ IRAC

- Simple adaptive control technologies can provide real benefits without undo complexity
- Adverse pilot/adaptive system interactions can be mitigated and tools have been developed to evaluate those interactions

◆ ICP

- Substantial fuel savings can be achieved over a broad range of vehicles and configurations with intelligent control solutions

◆ LVAC

- The AAC design is robust and effective for the SLS mission, and promises to provide benefits to other platforms as well

◆ OCLA

- Hopefully will show that structural feedback can be seamlessly integrated with performance and stability objectives

- ◆ **All of these control technologies have been implemented into the same baseline control law and could be combined into one control solution that answers many pressing questions for modern vehicle configurations**



Publications



◆ IRAC

- C. Miller, “Nonlinear Dynamic Inversion Baseline Control Law: Architecture and Performance Predictions,” in AIAA Guidance, Navigation, and Control Conference, Portland, Oregon, 2011.
- C. Miller, “Nonlinear Dynamic Inversion Baseline Control Law: Flight-Test Results for the Full-scale Advanced Systems Testbed F/A-18 Airplane,” in AIAA Guidance, Navigation, and Control Conference, Portland, Oregon, 2011.
- Hanson, Curt, Jacob Schaefer, John J. Burken, Marcus Johnson and Nhan Nguyen, Handling qualities Evaluations of Low Complexity Model Reference Adaptive Controllers for Reduced Pitch and Roll Damping Scenarios, AIAA 2011-6607, August 2011.
- Schaefer, Jake, Curt Hanson, Marcus Johnson and Nhan Nguyen, Handling Qualities of Model Reference Adaptive Controllers with Varying Complexity for Pitch-Roll Coupled Failures, AIAA 2011-6453, August 2011.
- Pavlock, Kate, David N. Larson and James L. Less, Flight Test Approach to Adaptive Control Research, SETP, September 2011.
- Pavlock, Kate, Full-Scale Advanced Systems Testbed: Ensuring Success of Adaptive Control Research through Project Lifecycle Risk Mitigation, SFTE, 2011.
- Nguyen, Nhan, John Burken and Curtis Hanson, Optimal Control Modification Adaptive Law with Covariance Adaptive Gain Adjustment and Normalization, AIAA 2011-6606.
- Hanson, Curtis E., Jacob Schaefer, Marcus Johnson, and Nhan Nguyen, Design of Low Complexity Model Reference Adaptive Controllers, NASA TM-2012-215972, May 2012.
- Hanson, Curtis E., An Ad-Hoc Adaptive Pilot Model for Pitch Axis Gross Acquisition Tasks, NASA TM-2012-216031, September 2012.
- Hanson, Curt, Jacob Schaefer, John J. Burken, David Larson and Marcus Johnson, Complexity and Pilot Workload Metrics for the Evaluation of Adaptive Flight Controls on a Full Scale Piloted Aircraft, NASA TM-2014-216640, February 2014.

◆ ICP

- Schaefer, J., and Brown, N., “Peak-seeking Optimization of Trim for Reduced Fuel Consumption: Architecture and Performance Predictions” AIAA-2013-4856, 2013,
- Brown, N., and Schaefer, J., “Peak-seeking Optimization of Trim for Reduced Fuel Consumption: Flight Test Results” AIAA-2013-5171, 2013,

◆ LVAC

- T. VanZwieten, E. Gilligan, J. Wall, , J. Orr, C. Miller, C. Hanson, “Adaptive Augmenting Control Flight Characterization on an F/A-18,” in AAS Guidance, Navigation, and Control Conference, Breckenridge, CO, AAS 14-052, 2014.



Backup Charts

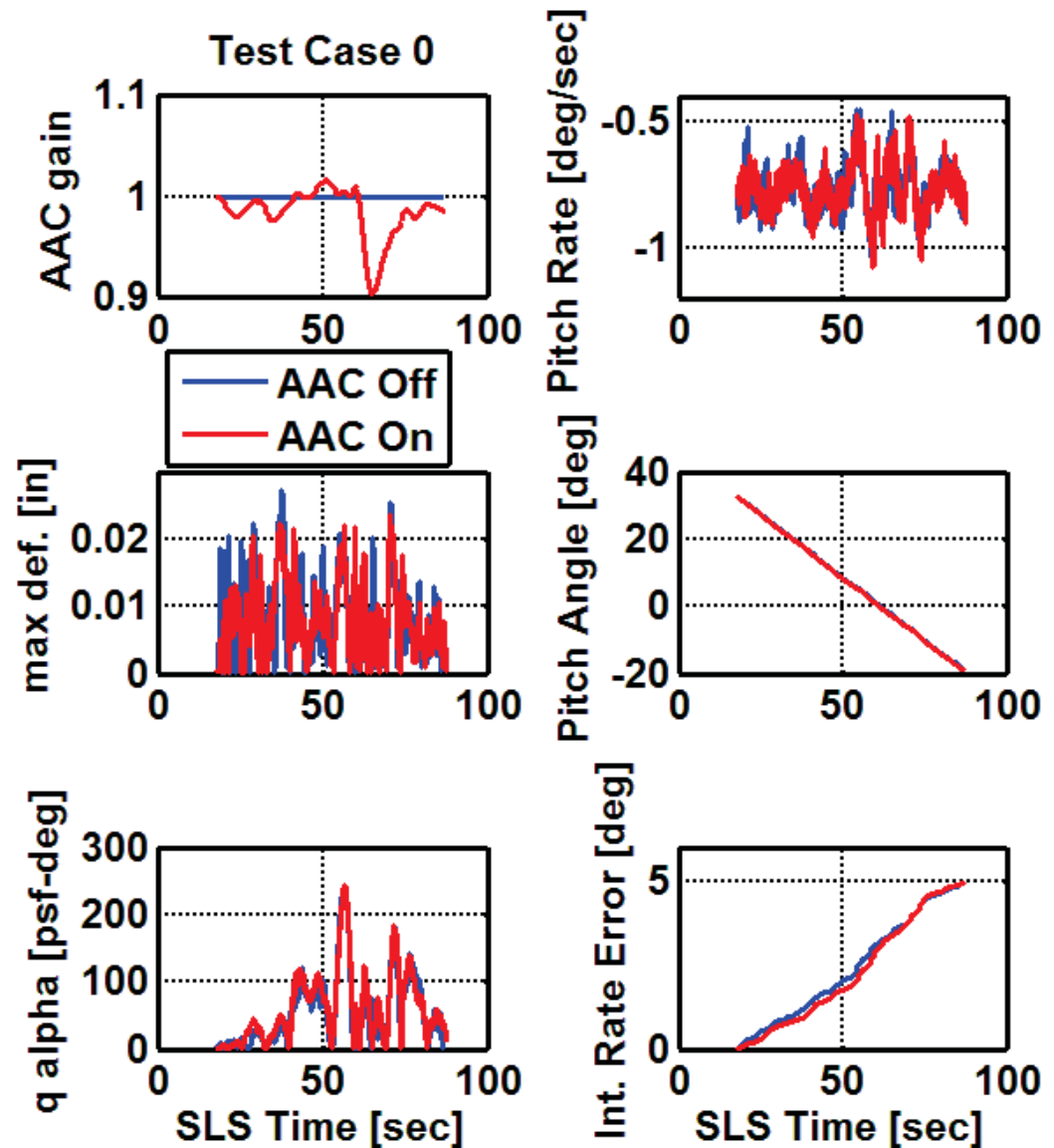




Minimal Adaptation in the Nominal Case



- ◆ Demonstrate Minimal Adaptation
- ◆ TC 0 – No Failures, Nominal Winds
- ◆ Fully demonstrated the objective
- ◆ Anomalies
 - Throttle transient more severe in flight than in the HILS
 - Smoothed out throttle position piloting technique
 - Caused the adaptive gain to drop which was not expected behavior





Improved Tracking Performance



- ◆ Demonstrate Improved Tracking
- ◆ TC 7 – Wind Shear and two simultaneous TVC hardovers
- ◆ Fully demonstrated the objective
- ◆ No anomalies

